

# *Smelting Iron from Laterite: Technical Possibility or Ethnographic Aberration?*



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## INTRODUCTION

LATERITES DEPOSITS (or lateritic soils as they are also called) are frequently reported in Southeast Asia, and are ethnographically attested to have been used for the smelting of iron in the region (Abendanon 1917 in Bronson 1992:73; Bronson and Charoenwongsa 1986), as well as in Africa (Gordon and Killick 1993; Miller and Van Der Merwe 1994). The present authors do not dispute this evidence; we merely wish to counsel caution in its extrapolation. Modifying our understanding of a population's potential to locally produce their own iron has immediate ramifications for how we reconstruct ancient metal distribution networks, and the social exchanges that have facilitated them since iron's generally agreed appearance in Southeast Asian archaeological contexts during the mid-first millennium B.C. (e.g., Bellwood 2007:268; Higham 1989:190).

We present this paper as a wholly constructive critique of what appears to be a prevailing perspective on pre-modern Southeast Asian iron metallurgy. We have tried to avoid technical language and jargon wherever possible, as our aim is to motivate scholars working within the region to give further consideration to iron as a metal, as a technology, and as a socially significant medium (e.g., Appadurai 1998; Binsbergen 2005; Gosden and Marshall 1999). When writing a critique it is of course necessary to cite researchers with whom one disagrees, and we have done this with full acknowledgment that in modern archaeology no one person can encompass the entire knowledge spectrum of the discipline.<sup>1</sup> The archaeometallurgy of iron is probably on the periphery of most of our colleagues' interests, but sometimes, within the technical, lies the pivotal, and in sharing some of our insights we hope to illuminate issues of benefit to all researchers in Metal Age Southeast Asia.

Since commencing research on Southeast Asian archaeometallurgy, the lead author has been concerned by a tendency to assume that laterite deposits are rich in iron oxide and/or that the presence of these deposits indicates the ready availability of an iron ore source for on-site or local smelting (e.g., Bronson 1992:66; Freeman and Jacques 1999:28; Higham 1989:Figure 4.1; Higham and Thosarat

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1998:135, 139; Källén and Karlström in Nitta 2003:170; Moore and Win 2007:205; Nitta 1997:158; O'Reilly 2007:543; Stone 2006:1364). Bronson does later qualify his claim with the necessary caveat of ore quality (Bronson 1992:75) and Nitta (1997) does perform the required analyses to demonstrate the likelihood of laterite smelting in a specific instance, but generally, the notion of lateritic iron ores seems to have become overly entrenched in the minds of archaeologists working within the region. Statements like, "iron ore is much more widespread than the ores of tin and copper in Southeast Asia ..." (Higham 1989:190) may be true (though cf. Sitthithaworn 1990 where economic Thai iron reserves are far outnumbered by tin mineralizations), but "... the [Khorat] plateau itself is rich in deposits of iron ore ..." (Higham 1996:188), which seems to refer to largely untested laterite deposits, is perhaps an overextension of Nitta's (1991, 1997) Ban Don Phlong findings.

The Oxford English Dictionary's definition of an "ore" is, "A naturally occurring solid material containing a precious or useful metal in such quantity and in such chemical combination as to make its extraction profitable" ([www.oed.com](http://www.oed.com), accessed 29 May 2008). We emphasize that "ore" is strictly a cultural term that may be applied to a natural mineral. A mineral may be considered an ore when people attempt to extract metal from it, "profitably" in modern parlance, but there are many potential motivations. Archaeological use of the term "ore" should therefore be substantiated by demonstrating, or at least reasoning, that past metalworkers were extracting metal from the mineral to which they refer.<sup>2</sup> This distinction is important as reappraising metallurgical resource distribution may have profound implications for past socioeconomic landscapes.

#### LATERITE

What is laterite? First coined in the early nineteenth century, the term "laterite" was long ago noted by Pendleton (1941:177) to have acquired some diversity of definition. A review of the geological literature indicates that laterites result from the decomposition and leaching of igneous, metamorphic, and sedimentary rocks within a dynamic tropical environment, and are frequently found in Africa, South America, South Asia, and Southeast Asia in both eluvial (primary) and alluvial (secondary) deposits (Aleva 1994; Braucher et al. 1998a, 1998b; Kasthurba et al. 2007; Pendleton 1941; Takimoto and Suzuka 1968). This wide range of origins results in extreme chemical and microstructural variability between materials that share the same name, and there can be further vertical and horizontal heterogeneity within a single deposit due to the vagaries of localized formation processes (Braucher et al. 1998b:1501). It is clear that there is no one "laterite."

Laterites have been widely used as a durable building material, with the unusual property that although typically soft when extracted, they harden irreversibly when exposed to air (Kasthurba et al. 2007:74; Pendleton 1941:200). Laterites have been briefly considered as a potential iron source in the recent past (Read 1937), but have more commonly been exploited as sources of nickel (Ni) and aluminium (Al). The iron<sup>3</sup> content of laterites can be lower than 1wt.% (weight percent, or proportion by molecular mass) but typically contains 15wt.% to 30wt.% (Aleva 1994:6; Kasthurba et al. 2007:Table 3), as well as a host of other contaminants. Therefore, whether a laterite is "rich in iron," "iron-rich," or "iron-laden" is necessarily relative (Bellwood 2007:11; Higham and Thosarat

1998:139; Moore and Win 2007:205). Only a small percentage of iron is required to give a substance a red/brown color, and the superficial appearance of an ore; a more reliable indicator is density, as an ore must contain heavy metal within it—a point shared by Biringuccio:

Good ore must be clear, heavy, and firm of grain, free from earth, stone, and all traces of any other kind of metal. (1540, translated by Smith and Gnudi 1990:66)

*Beneficiation*, or “making good,” is a metallurgical practice of millennia, and is a means of artificially increasing the metal content of a mineral. Using physical properties such as color, density, and fracture, the desired ore can be manually separated from unwanted host rock (*gangue*). This reduces the amount of waste material that must be dealt with at high temperature, and can concentrate previously unusable minerals to a quality that can be smelted. Laterites cannot easily be beneficiated due to the wide dispersion of iron throughout the material, in chemical rather than mechanical association with other elements. Attempts to crush friable laterites commonly result in a red dust from which the iron-rich component cannot be recovered without hydraulic density separation and powder binding techniques (Gordon and Killick 1993:267).

#### IRON SMELTING

We emphasize that there can be almost infinite variety in metallurgical technique and sociotechnical practice—ethnically, geographically, and temporally—best attested by the enormous amount of research deriving from African iron production (e.g., Killick 2004*b*; Mapunda 2000; Rehren et al. 2007; Schmidt 1997). This variability is welcome, as without it we would not be able to define technological styles and delineate networks of technological transmission (e.g., Charlton et al. 2010; Killick 2004*a*; Kuhn 2004). However, there do remain some universal physico-chemical constants, which dictate that for the smelting of iron to occur, certain criteria must be fulfilled. Chief amongst these is the quality of ore mineral required for iron bloomery production. Here, by quality, we mean the proportion of the mineral that is iron. The main contention of this paper is that laterites in Southeast Asia typically do not contain enough iron for bloomery smelting, nor can they be easily beneficiated to increase this iron content. As such we only reaffirm regional mineralogical affordances recognised 70 years ago, “The occurrences of high-grade ore [in Malaya] are quite distinct from the concretionary deposits of ironstone, very wide-spread throughout Malaya [and Southeast Asia generally], but too shallow and containing too low a content of iron to be of commercial value as iron ore. The concretions are known as “laterite” (Harris and Willbourn 1940: 25). Therefore, we urge the reader to exercise caution when contemplating the location of potential iron sources in mainland Southeast Asia.

This article is not the place for an in-depth explanation of iron bloomery smelting processes. There are already a number of authoritative texts on this subject (e.g., Buchwald 2005; Craddock 1995; Pleiner 2000; Tylecote 1992), but in gross simplification, it is the production of iron in the solid state (i.e., the iron metal doesn’t melt), as opposed to blast furnaces that produce liquid cast/pig iron. The purpose of the bloomery smelt is to reduce iron oxides to metallic form (reduction is the removal of oxygen), and separate the metal from associated impurities—refractory aluminosilicates from the gangue and decomposing technical

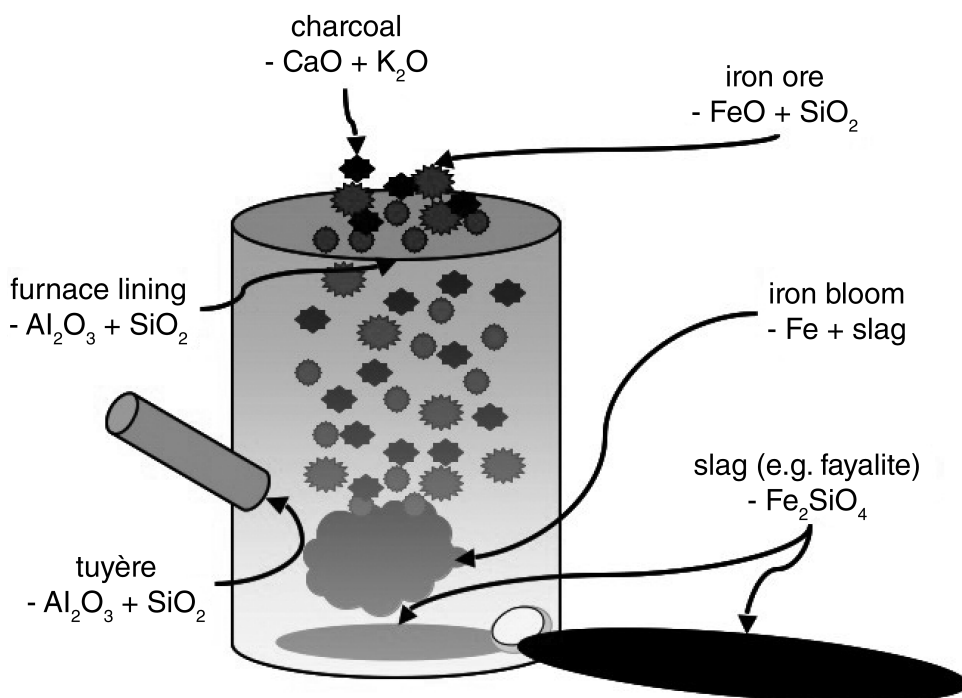


Fig. 1. Schematic of a generic bloomery smelting furnace, showing the principal major oxides contributed to the slag by components of the smelting system.

ceramics are fluxed by alkalis from the fuel ash and iron oxide from the ore mineral (Fig. 1). The resulting material is liquefied within the bloomery furnace, and can flow away from the newly formed, and unmelted, iron (Fig. 1). This by-product is familiar to most archaeologists as *slag*, which, although it can occur with many morphologies and chemistries, is rightly interpreted as representing some sort of high-temperature activity.

The product of the bloomery smelt is the *bloom*, a typically sponge-like conglomerate of iron and residual slag which forms on the interior furnace wall (Fig. 1). This bloom must then be smithed or forged with a hammer (hence *wrought iron*) to squeeze out the remaining slag. The consolidated and homogenized metal is then known as a *billet*, and is ready for forging into any number of the amorphous rusty forms we encounter on our excavations and surveys. Elongated slag inclusions, or *stringers*, are always present to some degree in wrought iron as the smithing process is never complete.

Bloomery smelting is the general term for the method of iron extraction universally attested around the world, and in all iron producing and consuming societies, until the advent of blast furnaces in medieval Europe, and much later in many places. The very notable (and relatively local) exception is China, where the earliest hard evidence for blast furnaces derives from second century B.C. Han contexts (Jianjun Mei pers. comm.; Wagner 1993). Fortunately, bloomery and blast production processes produce waste products which can be easily distinguished by an archaeometallurgist. There is at present no evidence for an early introduction of Chinese blast technology to Southeast Asia where iron production

TABLE 1. THEORETICAL IRON METAL YIELDS FOR DIFFERENT GRADES OF SILICEOUS IRON ORE.

100 kg IRON ORE FeO (wt.%)	POTENTIAL BLOOM Fe (kg)
70	none
75	12
80	25
85	38
90	51

seems to have involved only bloomery techniques (Bronson 1992; Pigott 1986; Suchitta 1983, 1992).

With very few exceptions, bloomery smelting cannot work without the production of slag (Fig. 1). Iron metal has a high affinity for oxygen, and will oxidize very quickly at smelting furnace temperatures (c. 1150–c. 1450 °C). The slag performs an essential function in forming a protective bath around the bloom, preventing hot oxygen gas in the combustion zone of the furnace from reacting with the newly-formed iron metal. The slag also serves the function of concentrating unwanted impurities from the smelting system (gangue, technical ceramic, fuel ash), improving the quality of the metal product. The chemical composition of slags can vary significantly, but for bloomery smelting the normalized major slag components are silica ( $\text{SiO}_2$  c. 30wt.%) and iron oxide ( $\text{FeO}$  c. 70wt.%) (Rehren et al. 2007). That is, iron smelting by the bloomery process requires iron to produce the necessary slag *as well as* the desired metal. Thus it follows that the iron ore needed by bloomery operators contained at least 70wt.% of  $\text{FeO}^4$ . Considering that 15wt.% to 30wt.%  $\text{FeO}$  is the norm, this amount of iron oxide is unlikely to be common in Southeast Asian laterites (Aleva 1994:6; Pendleton 1941:202).

The significance of ore quality is further demonstrated by the ‘break point’ seen in Table 1. Theoretically, at 70wt.%  $\text{FeO}$  one might expect no iron to be produced, but at 75wt.%  $\text{FeO}$  the optimal metal yield is c. 12 kg, and at 80wt.%  $\text{FeO}$  one might extract c. 25 kg of iron. That means increasing the ore quality by only 5wt.% (75–80) can more than double the potential yield of useful metal. The above calculations assume reactions in standardized conditions that proceed to equilibrium, circumstances uncommon in the real world, but the figures are certainly indicative of the sensitivity of successful bloomery smelting to ore quality.

Whilst slag is a common find on archaeological sites, unless it can be demonstrated to result from iron *smelting*, the default interpretation must be iron *smithing* or *forging*. Indeed, the enormous quantities of slag normally produced by smelting activities rarely leave any ambiguity in the matter—as seen at Ban Don Phlong and Ban Di Lung in Thailand (Higham 1996:225; Nitta 1991, 1997; Suchitta 1983, 1992). It is the smithing process that produces ‘Smithing Hearth Bottoms’ (SHBs; Pryce et al. 2008:Fig. 1); the ubiquitous and morphologically highly standardized (globally in all iron-using contexts) plano-convex slags frequently found on Southeast Asian sites of appropriate periods.

#### A CASE STUDY FROM BAN KAO DIN TAI

Ongoing excavations by the Living Angkor Road Project at Ban Kao Din Tai, a fourteenth- to fifteenth-century A.D. site in Amphoe Ban Kruat, Changwat

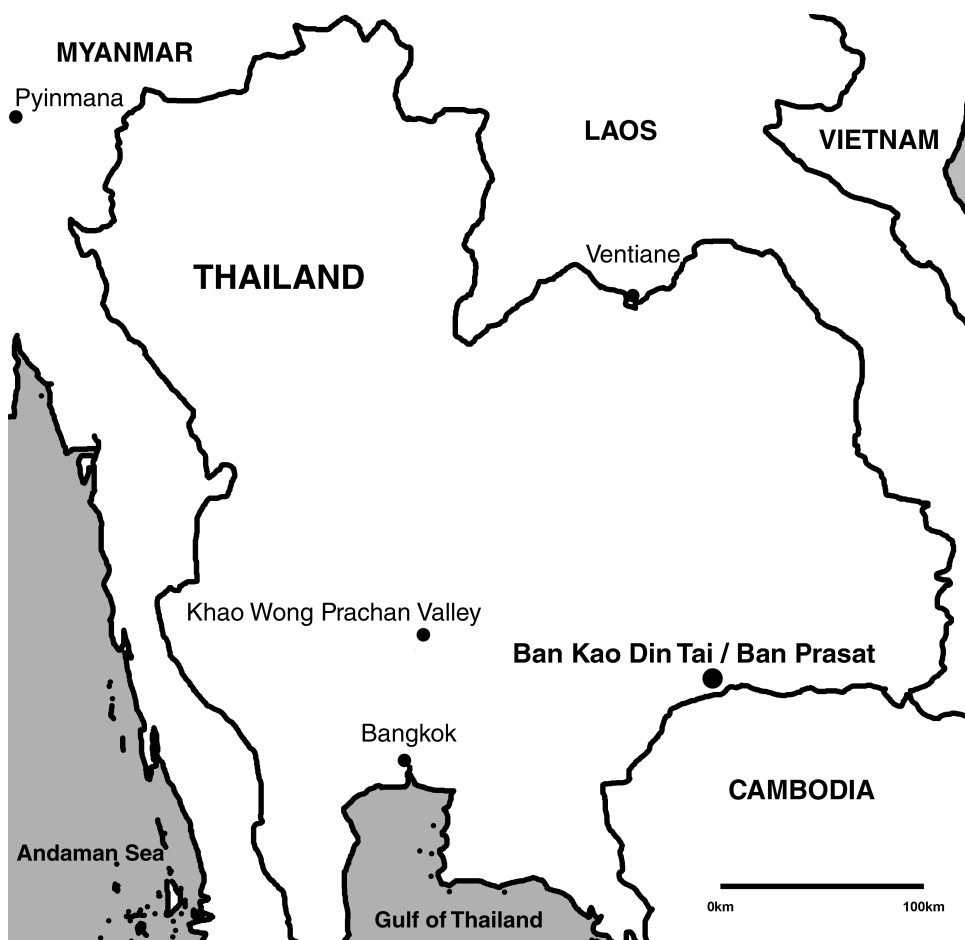


Fig. 2. Map showing Thai archaeological and geological sites mentioned in the text; adapted from Sitthithaworn (1990).

Burirum, have uncovered what appear to be a number of iron smelting furnaces, with associated finds of slag and laterite fragments. Amphoe Ban Kruat is an area known to contain extensive deposits of laterite, with a local concentration at Ban Prasat (Fig. 2). The archaeological site at Ban Kao Din Tai is under ongoing excavation and its investigators kindly permitted the lead author to make use of their material to demonstrate the regional laterite/iron smelting issue. The archaeometallurgical research question is: do the laterite fragments recovered from the Ban Kao Din Tai excavation contain enough iron to have conceivably been used as an ore for smelting at the site? Thus, can we consider the likelihood that metal workers at Ban Kao Din Tai produced iron metal from locally available laterite deposits?

#### *Method*

Four laterite samples were sent to London for bulk compositional analysis: two samples from the archaeological site Ban Kao Din Tai (BKDT1 and 2) and two

samples from the geological deposit Ban Prasat (BP3 and 4). Also prepared for comparative purposes was an iron oxide (magnetite) sample, KTKM1, from Khao Tab Kwai in the Khao Wong Prachan Valley, Changwat Lopburi (Fig. 2)—known to have been used as a source of bloomery iron ore (Suchitta 1983).

The outer surfaces of the samples were cut away prior to cleaning in an ultrasonic bath. The samples were dried, before crushing to a 50  $\mu\text{m}$  analytical powder in a planetary mill. The powder was then mixed with a wax binding agent before pressing into pellets.

The pellets were analyzed using Polarising Energy Dispersive X-Ray Fluorescence ([P]-ED-XRF) on a Spectro X-Lab Pro 2000 unit. The samples were processed according to standard practices for the Wolfson Laboratories at the UCL Institute of Archaeology, operating the XRF unit with the general geological algorithm “Turboquant.”<sup>5</sup>

### *Results and Interpretation*

The data presented below are the averaged results of the [P]ED-XRF analysis, for stoichiometrically balanced (combined with oxygen) constituents above 1wt.% (Table 2).

The data show that the iron levels (46.4wt.% and 36.5wt.%) of the laterite samples from Ban Kao Din Thai are insufficient for the generally held limitations of bloomery smelting—the mineral iron oxide used in the smelt must contain enough iron to produce the requisite slag, with only the excess being available for extraction as iron metal (Table 1). The data also show that the laterite samples from Ban Prasat contain enough iron oxide (57.9wt.% and 65.5wt.%) to constitute borderline iron ores. By way of comparison, the magnetite sample KTKM1 from the Khao Wong Prachan Valley is an example of a high quality Thai iron oxide mineral.

While the implications of this preliminary analytical study may appear superficially negative—the excavated laterite from Ban Kao Din Tai was not bloomery smelt-able—there are several interesting suggestions we can make:

1. Considering the ancient metal workers were presumably more skilled at choosing their ore minerals than archaeologists, it is conceivable that the Ban Prasat source could have been mined (and perhaps fully depleted) for laterite of sufficient quality by smelters at Ban Kao Din Tai—although they would be operating at the technical limits of the bloomery process.

TABLE 2. BULK (P)ED-XRF CHEMICAL DATA FOR LATERITE SAMPLES FROM BAN KAO DIN TAI AND BAN PRASAT, PLUS A MAGNETITE SAMPLE FROM THE KHAO WONG PRACHAN VALLEY.

	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	FeO	TOTAL	Al <sub>2</sub> O <sub>3</sub> :SiO <sub>2</sub>
BKDT1	8.8	36.8	1.0	0.2	0.4	46.4	<b>93.6</b>	0.24
BKDT2	11.7	45.3	0.2	0.0	0.5	36.5	<b>94.1</b>	0.26
BP3	7.4	26.0	0.2	0.0	0.3	57.9	<b>91.8</b>	0.28
BP4	8.1	17.3	0.3	0.0	0.3	65.5	<b>91.5</b>	0.47
KTKM1	1.5	1.8	0.3	0.1	0.1	85.3	<b>89.0</b>	0.84

2. It is also reasonable to suggest that the archaeologically-recovered laterite was rejected by skilled and experienced Ban Kao Din Tai smelters due to its unsatisfactory iron oxide content; the acceptable laterite having been converted to metal and slag. Considering the amount of labor that goes into acquiring ore minerals, they are not likely to be discarded negligently.

3. Although we have already argued against the efficacy of beneficiating laterites, there is strong ethnographic evidence from Africa that low-iron laterites can be smelted given specific criteria (Miller and Van Der Merwe 1994:24).

The technical mechanism for this process has been firmly established in Kasungu, Malawi, by Robert Gordon and David Killick (1993:263). Ethnoarchaeometallurgical investigations revealed that local smelters could extract metal from laterites containing only 20wt.% to 30wt.% iron, by selecting only those materials that contained uniformly large grains of silica. Established archaeometallurgical principles have often been derived from modern industrial knowledge, which expect that chemical reactions are both complete and uniform—a paradigm into which archaeology rarely fits. Silica, in the absence of fluxing materials (e.g., iron oxide) has a melting range c. 1720 °C; a temperature unachievable over large volumes or extended periods of time in pre-industrial furnaces. Therefore, by choosing laterites with large grains of silica that could not fully react in the furnace, the smelters were effectively isolating this component from the smelting chemistry. This unreacted silica did not then require iron oxide to form a slag, thus liberating iron which could form in the bloom (Gordon and Killick 1993). This is but one archaeometallurgical example among many demonstrating that ‘suboptimal’ and ‘inefficient’ methods can achieve technical outcomes that modern science deems unlikely. Whether smelting techniques similar to the Malawian example have ever been employed for the exploitation of Southeast Asian laterite is at present unknown.

#### DISCUSSION

Although four mineral samples cannot definitively determine the veracity of laterite-based bloomery smelting at Ban Kao Din Tai, we have been able to indicate its potential likelihood in this instance, with the Ban Prasat laterite samples approaching the level of iron oxide needed. Further evidence for laterite smelting might be sought in the typically high ratio of alumina to silica ( $\text{Al}_2\text{O}_3:\text{SiO}_2$ ) found in laterites (Aleva 1994). Were laterite to be used as an iron ore we might expect the high ratios seen in Table 2 to be transmitted to the bulk chemistry of smelting slags. However, this chemical relationship can be masked by slag contributions of alumina and silica from technical ceramics within the smelting system, and the only unequivocal evidence of laterite smelting is the identification of partially reacted laterite fragments within smelting slags (e.g., Gordon and Killick 1993:Fig. 4; Nitta 1997:156). Unfortunately, at the time of writing, slag samples from Ban Kao Din Tai were not available for analysis, but ongoing study will hopefully establish whether the slag at the site did indeed result from the smelting of local laterites. This archaeometallurgical consideration should help determine the socioeconomic basis of the area (cf. Mudar and Pigott 2003), and contribute towards better understanding the way of life of past inhabitants and their involvement in the wider Khmer world.



*Whence Premodern Southeast Asian Iron, and the Future of Regional Ferrous Archaeometallurgy?*

For Southeast Asia in general, we propose that scholars who suspect laterite-based smelting activities should routinely conduct microstructural and compositional analyses on samples from local laterites deposits and slags from their sites. There is no doubt that some laterites can be smelted, and that in some cases they were (e.g., Abendanon 1917 in Bronson 1992:73; Nitta 1997; Pendleton 1941:202), but we regard it as unsafe to regard all Southeast Asian laterite deposits as potential or actual sources of pre-modern iron (cf. Bronson 1992:66).

What then is the effect of a reconsideration of regional iron ore availability? Figure 3 indicates the known major economic iron ore sources in Thailand. This map must be modified by the addition of minor uneconomic (in the modern sense) sources, and of course those locales where laterites contain enough iron to



Fig. 3. Map showing modern economic sources of iron oxide in Thailand; adapted from Sitthithaworn (1990).

be smelted by bloomery furnaces. However, we are never going to be in a position where the distribution of iron ore sources is such that most pre-modern archaeological sites could have locally sourced their iron (contra Bronson 1992:66).

This geographical/geological issue should be combined with a consideration of skill. As the English philosopher Joseph Glanville said in the mid-seventeenth century, “iron seemeth a simple metal but in its nature are many mysteries . . .” The extraction of iron from its ores is relatively easy to grasp in theory, but to consistently produce usable metal is considerably harder in practice (Read 1934:387), requiring extensive apprenticeship and empirical experience (e.g., Crew and Crew 1997; Jarrier et al. 1997; Serneels and Crew 1997). Successful iron technologies may vary in terms of technique, scale, and social context (*sensu* Costin 1991, 2001), but they are always skillful. We wish to express our reservation at unduly mechanistic considerations of iron production and consumption, which confine themselves to associations with improved agricultural and martial potential (e.g., Higham and Thosarat 1998:170), or assume that “iron working was a process that could be carried out easily by small, local communities and that knowledge of its manufacture spread rapidly . . . , as the superior economic potential and easier availability of this metal—compared to bronze—was realised” (Bellwood 2007:286).

These widespread perspectives appear to derive originally from Childe’s (1942) notion of iron “democratising” metallurgy (see also Budd and Taylor 1995:140), and are to an extent true, but don’t account for the less utilitarian aspects of the human/metal interaction (e.g., Barndon 2004; Gansum 2004; Giles 2007; Haaland 2004; Källen 2005.<sup>6</sup> Due to the probable low co-incidence of resources and skill, we propose that at most Southeast Asian archaeological sites, the mere presence of iron artifacts is likely to be evidence for social interaction and exchange networks, to some degree.

Many scholars who have worked on Metal Age sites may have experienced a degree of anticlimax when confronted with archaeological iron artifacts; a feeling sometimes shared by archaeometallurgists. Rusty, fragile, and typologically frustratingly functional, iron artifacts can nevertheless preserve a surprising amount of information. Researchers in Southeast Asian metallurgy have for many years been conducting microstructural analyses, which, even in corroded matrices, can provide us with evidence of variable forging techniques, a key style marker for defining metallurgical traditions (e.g., Bennett 1982; Dizon 1990; Sukawasana 1991). However, we wish to draw the reader’s attention to an analytical methodology, which, although not new, is undergoing rapid development in other parts of the world.

*Stringers* are the elongated smelting slag inclusions which remain in artifacts due to the imperfect homogenisation of wrought iron. Slag Inclusion Analysis (SIA) is a technique being explored to find geochemical correlations between iron artifacts, smelting sites, and iron ore bodies, and which, excepting an exploratory attempt by Anna Bennett in the early 1980s has never been employed in Southeast Asia (e.g., Coustures et al. 2003; Desaulty et al. 2009; Dillmann and L’Héritier 2007; Paynter 2006; Salter 1976; Schwab et al. 2006; Veldhuijzen and Rehren 2007). Typically, a microprobe or SEM-EDX, LA-ICP-MS, or SEM-EDS system is used to characterize the slag inclusions within an artifact by their chemical composition. The slag analyses for iron artifacts can then be compared within and be-

tween assemblages to look for archaeologically relevant patterning; i.e., does it appear as though all the iron from one period at a site came from one or multiple sources?

Like all techniques, SIA has its problems, and the first of these is that the chemical and microstructural characteristics of a stringer are not stable, and will change as the metal is repeatedly forged and repaired. This shifting signature is mainly due to the increasing contribution of fuel ash to the slag at each heating cycle, and the ongoing loss of iron through oxidation (the sparks one sees in a smithy are particles of red hot iron oxide flaking off the surface of the metal). The second issue is that the comparison of slag inclusions can only produce groups of iron artifacts, but cannot provenance them as this would require a database of source variation, and for iron ores this database is unmanageably large (cf. for Mediterranean copper in Knapp 2000). The latest SIA research suggests sourcing iron metal to a particular ore is not feasible anyway due to the overlapping chemistries of the hot smelting system (technical ceramics, fuel ash, fluxes, and gangues) obscuring the original ore signature (Desaulty et al. 2009; Serneels et al. 2008; Blakelock et al. 2009). However, it is proving possible to provenance to the level of the smelting system, and in human terms this means the materialization of collective decisions and actions taken at the smelting site level.

Therein lies the challenge for Southeast Asian ferrous archaeometallurgy—the characterization of smelting systems. Previous studies by Suchitta (1983, 1992) and Nitta (1991, 1997) at Thai iron smelting sites need to be consolidated by the long-term systematic examination of pre-modern iron smelting sites across Southeast Asia—in Thailand one might well start with a survey of every *Ban Khi Lek* (Iron Slag Village) on the map. Not only would this research provide the underlying database to complement SIA studies on iron exchange, but it would also place these important technologies within their proper historical and anthropological context. A comprehensive technological approach to iron is also the requisite route to broaching the issues of the origins and transmission dynamics of Southeast Asian ferrous metallurgy (Bellwood 2007:274); be it indigenous, East Asian or South Asian, adopted or adapted, imitated or inspired; nuance and intrigue are guaranteed.

## CONCLUSION

The Living Angkor Road project is an excellent example of how archaeometallurgical issues can be wholly intertwined with questions of wider archaeological interest. The technical question of whether local laterites were bloomery smelted at Ban Kao Din Tai is one of relevance to many sites within the region. Iron may be a more commonly occurring metal than copper, gold, and tin (Bronson 1992:66) but archaeologists working in Southeast Asia should not assume that this seemingly unattractive and utilitarian material is universally available in the form of laterite. An improved understanding of the sparse distribution of high quality iron deposits, and the skill required to extract the metal, suggests there may have been relatively few iron smelting centres in operation, and that their product, as bloom, billet, or finished artifact, was circulated to many consumption areas, where the presence of smithing slags (SHBs) would indicate the onsite forging of artifacts or their repair. Therefore, we hope that the presence of iron at a

site will incite scholarly curiosity rather than aesthetic distaste and conservation despair. A population's decision or tradition of iron use could stimulate an insightful consideration of their need or desire for the metal, and subsequent participation in (potentially long distance) regional exchange networks to acquire it.

#### ACKNOWLEDGMENTS

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#### ENDNOTES

1. We particularly acknowledge Bronson's (1992) commendably comprehensive review of South-east Asian metallurgy.
2. It is terminologically impossible for a copper smelting operation to be fluxed with "iron ore," the metal being extracted is copper and thus the flux is simply iron oxide (contra Higham 1996:137).
3. There are three oxidation states of iron that are of interest in archaeometallurgy:  $\text{Fe}^{[0]}$  ferrite or iron metal,  $\text{Fe}^{[2+]}\text{-FeO}$  or wüstite,  $\text{Fe}^{[3+]}\text{-Fe}_2\text{O}_3$  or haematite, and the intermediary compound  $\text{Fe}^{[2+/3+]}\text{-Fe}_3\text{O}_4$  or magnetite. All numerical data in this paper has been converted to either Fe, iron metal, or FeO, iron oxide, for the sake of simplicity.
4. There are exceptions to this high iron content requirement for bloomery ores, but they remain to be demonstrated in Southeast Asia. In essence, the iron in the slag can, to a varying degree, be substituted by calcium or manganese; increasing the amount of iron that can be extracted as metal product.
5. Certified Reference Materials (CRMs) were also scanned to assess the accuracy and precision of the XRF analysis. Error levels were safe considering the compositional resolution needed.
6. In this article we have advised analogical caution for local ethnographic and archaeological data; thus the African and European-based references are indicative of interpretive potential only.

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#### ABSTRACT

The existing Southeast Asian archaeological literature commonly presupposes that the region's extensive laterite deposits are rich in iron and have been used as ore sources for the smelting of iron. We summarize what is known about laterite in light of the universal physico-chemical requirements for the bloomery smelting of iron, and suggest that in each instance the interpretation of laterite as an iron ore should be proven and not assumed. We present a case study from the fourteenth- to fifteenth-century A.D. site of Ban Kao Din Tai, recently excavated by Thai and Cambodian archaeologists in Buriram Province in northeast Thailand. The proximity of this site to known laterite deposits, along with the recovery of laterite fragments near what are thought to be smelting furnaces, could imply that past metalworkers were exploiting a local source of iron oxides for metal production. Here we discuss the likelihood of this association. If laterite is not a ubiquitous iron source for Southeast Asian iron production, then there is strong research potential to examine iron's possible role in regional exchange networks. Iron production and consumption evidence may provide an exciting new angle for investigating Southeast Asian social interactions, and we outline some of the analytical techniques that could elucidate them. KEYWORDS: archaeometallurgy, exchange networks, iron, laterite, smelting, smithing, Thailand.